ENVIRONMENTAL MEASUREMENT WHILE DRILLING (EMWD)

Subsurface Contaminants Focus Area and
Characterization, Monitoring, and Sensor Technology
Crosscutting Program

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INNOVATIVE TECHNOLOGY
Summary Report

ENVIRONMENTAL MEASUREMENT WHILE DRILLING (EMWD)

Tech ID 8

Subsurface Contaminants Focus Area and
Characterization, Monitoring, and Sensor Technology
Crosscutting Program

Demonstrated at

Savannah River Site
Aiken, South Carolina

Hanford Reservation
Richland, Washington

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that prospective users consider a technology.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under "Publications."

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SECTION 1
SUMMARY

Technology Summary

Having real-time data on drill bit location and subsurface contamination while drilling is important for safely and cost-effectively conducting many environmental remediation and restoration operations. An inexpensive data collection and documentation system would also reduce costs and, when combined with horizontal drilling, would provide inter-hole data missing when only vertical holes are used to sample the subsurface. In places, such as the Hanford tank farms, where using vertical holes to sample soil beneath tanks is not feasible, using horizontal drilling combined with a sensor system may be the only viable alternative to identify and measure contaminants.

Problem: Determining the presence and specific location of radioactive contamination under waste tanks, ponds, lagoons, and facilities without compromising the integrity of the contaminant source.

The baseline approach is subsurface sampling and off-site sample analysis. Samples of the subsurface are taken at frequent intervals. After preliminary screening with field instruments, the samples are packaged, documented, and sent to an off-site laboratory for analysis. Laboratory analysis is not only expensive, but obtaining the analytical results can take weeks or months. This time lag dramatically slows progress and further increases characterization costs.

The baseline approach involves conducting a comprehensive site characterization sampling strategy without benefit of real-time subsurface data. To measure the presence and location of contamination under targeted facilities, this approach would bore or otherwise penetrate, vertically or horizontally, into the area of interest to obtain samples for off-site laboratory analysis. Penetration of the contaminant source would compromise the integrity of any existing containment system. There would be no information on the presence or absence of radioactive contamination in the subsurface soil between the sampled intervals.

Solution: The Environmental Measurement While Drilling (EMWD) sensor delivery and data collection system is an enabling technology that was developed by Sandia National Laboratories (SNL) to provide real-time measurements of radiation and other environmental attributes in the subsurface under potential contaminant sources. The EMWD data collection system continuously records these measurements and their location. The screening capability of EMWD saves time and money and enhances worker safety by quickly distinguishing between contaminated and uncontaminated areas while leaving containment systems intact. EMWD can be used to minimize the number of samples needed to characterize the subsurface environment and reduce investigation-derived waste.

The EMWD system is a complete instrumentation system, which when coupled to a horizontal directional drilling rig, collects drill bit orientation and location data at the same time as it collects environmental data. By linking bit location with environmental data, a complete log of subterranean conditions can be mapped in real time. The real-time measurements provided by EMWD enable field personnel to make on-the-spot decisions regarding sampling and remediation strategies. Furthermore, EMWD makes it possible for operators to “steer” the drill bit into, out of, or around the periphery of hazardous zones. It enhances worker safety by alerting field personnel to potentially hazardous conditions. The system works in conjunction with various commercially available drill rigs.

Potential Markets: While EMWD was initially designed to locate, identify, and measure underground gamma emitters at U.S. Department of Energy (DOE) sites, its instrument suite can be augmented with sensors for detecting various chemicals and additional environmental attributes. Incorporating additional capabilities into the EMWD system would increase the number of uses and potential users. Some likely users would include other government agencies, such as the U. S. Environmental Protection Agency and Department of Defense, Resource Conservation and Recovery Act (RCRA) and Superfund sites, and operators of commercial and local government sites where subsurface contamination is a concern. Examples of sites that would benefit from subsurface characterization beneath the contaminant source include landfills and trenches, waste storage tank farms, chemical production and storage sites, power plants, pipelines, and contaminated facilities.

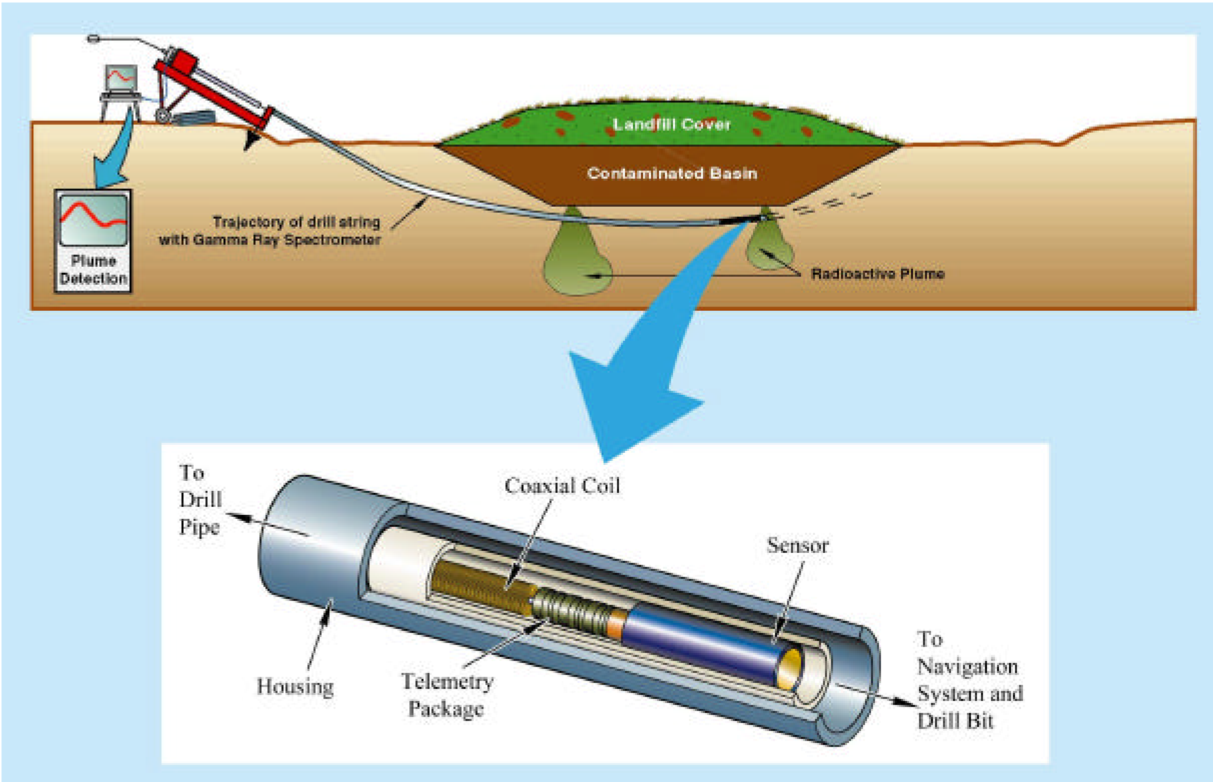

Figure 1. Illustration of Environmental Measurement While Drilling System (EMWD) developed by Sandia National Laboratories (SNL)

Demonstration Summary

During April 1996 the EMWD gamma ray spectrometer system (Figure 1) was successfully demonstrated at the Savannah River Site F-Area Retention Basin in South Carolina. The primary purpose of the demonstration was to compare the cesium-137 (Cs-137) data collected in real-time with the EMWD system to the data from the off-site analysis of soil samples obtained earlier by sampling conducted in vertical sampling holes. While drilling two horizontal boreholes below the backfilled retention basin, EMWD continuously monitored the soil for gamma radiation. The boreholes passed near previously sampled vertical sampling hole locations where there were known concentrations of Cs-137. The real-time results showed a strong correlation to the previously obtained laboratory results. In addition, two previously unknown areas contaminated with Cs-137 were also found and plotted by EMWD software. The pull back of the drill rod was successful in that it resulted in no radiation-contaminated equipment or waste brought to the surface.

In September and October 1998 the EMWD system was demonstrated in conjunction with horizontal directional drilling at the Mock Tank Leak Simulation Site and the Drilling Technology Test Site at the Hanford Reservation in Washington. The technology demonstration consisted of the development of one borehole under a mock waste tank at a depth of approximately -8 m (-27 ft.), following a predetermined drill path, tracking the drill path to within a radius of approximately 1.5 m (5 ft.), and monitoring for zones of expected natural radiological activity from potassium-40 (K-40) using the EMWD GRS system. The primary purpose of the second borehole was to demonstrate the capability to drilling to a depth of approximately -21 m (-70 ft.) and to continue drilling horizontally in difficult media likely to be encountered under the Hanford high-level waste tanks. Natural gamma emitters were also measured during drilling operations.

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Other
All published Innovative Technology Summary Reports are available on the OST Web site at http://apps.em.doe.gov/ost/ under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The Tech ID for Environmental Measurement While Drilling is 8.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

The Environmental Measurement While Drilling (EMWD) sensor delivery and data collection system developed by Sandia National Laboratories (SNL) is designed to obtain real-time data on drill bit location and environmental measurements during drilling. The objective of this system is to distinguish contaminated from non-contaminated areas in real time while drilling beneath a hazardous waste site. The downhole sensors are located behind the drill bit and linked by a high-speed data transmission system to a computer at the surface. As drilling is conducted, real-time data are collected on the nature and extent of contamination, thus enabling field personnel to make on-the-spot decisions regarding drilling and sampling strategies. The system provides real-time data on environmental conditions, drill bit location, and system health.

The EMWD system sensors include a gamma ray spectrometer (GRS) and an angular orientation sensor (3-axis magnetometer). The GRS consists of a thallium-activated, sodium-iodide (NaI) crystal coupled to a photomultiplier tube (PMT). The GRS output feeds to a multichannel analyzer (MCA). The 256-channel gamma spectrum (0.15-1.6 MeV) data are transmitted to the surface via a signal conditioning and transmitter board. A full gamma spectrum is transmitted to the surface every 20 seconds. The drill bit location is determined by tracking the bit heading (azimuth), tool face (role), and inclination (tilt) using the angular orientation sensor. Figure 2 shows the instrumentation mounting locations on a typical directional drilling rig. The readings from the GRS and the magnetometer are linked so that the position on contaminants is determined. Each of these readings is made every 2 seconds. Sampling speed from the analog channels can reach 100 kHz. The telemetry system is firmware programmable to easily support many different data formats and additional data channels. The data transmission format (digital frequency modulation [FM] bi-phase, 4,800 baud) provides excellent noise rejection for jumping the wireless

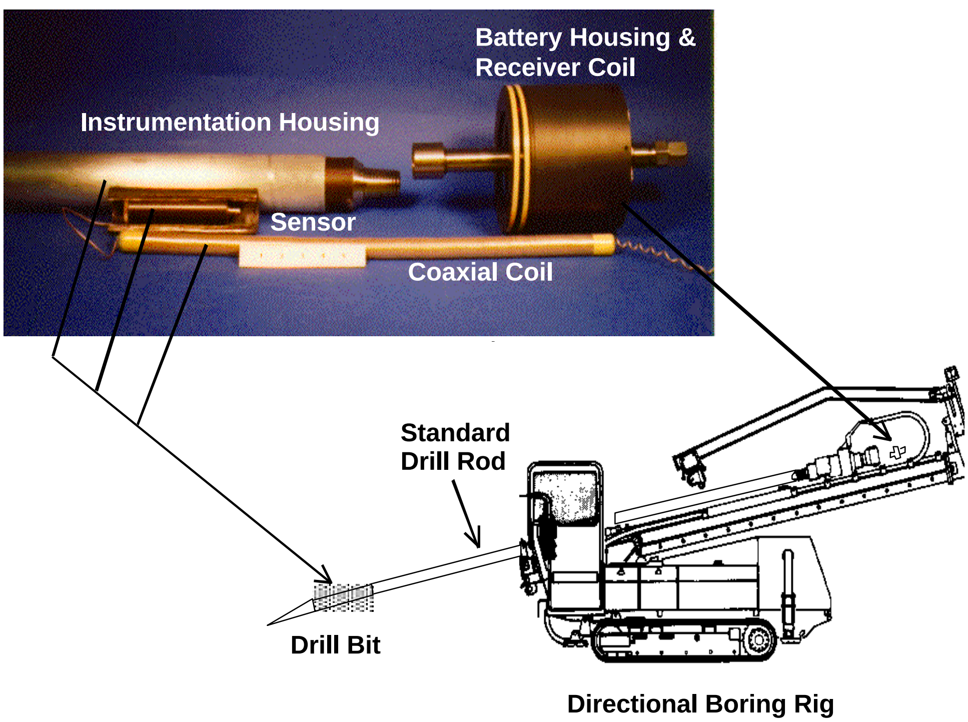

Figure 2. Environmental Measurement While Drilling (EMWD) Gamma Ray Spectrometer (GRS) System Component Placement on a Typical Horizontal Directional Drilling (HDD) Rig

connection between the rotating drill pipe and the stationary receiver. An SNL-designed receiver removes the FM carrier and buffers serial data to be used by a personal computer. A rechargeable battery pack supplies downhole instrumentation power for more than 20 hours of drilling. The battery pack remains uphole for easy maintenance and/or recharging.

The EMWD system also monitors the uphole battery voltage as measured downhole, and the temperatures associated with the detector and instrumentation. System health is the measurement of downhole battery voltage and temperature along with the more sophisticated measurements of magnetic interference and vibration. The EMWD system design includes data quality assurance techniques to increase safety by reducing the probability of giving a safe indication when an unsafe condition exists.

System Adaptability

The EMWD System is compatible with vertical, angle, or horizontal directional drilling techniques that use mud lubricant, water, or minimal drilling fluids. The system is compatible with Ditch Witch Fluid Miser™-lined drill pipe, an optional technique that uses minimal drilling fluids and generates little or no secondary waste.

The electronics package, located near the drill bit, is easily adaptable to different sensors or data formats. Adaptability is gained by using a programmable logic array (PLA). This small-surface mounted integrated circuit (IC) contains some 2,000 logic gates. The PLA controls the data-stream format, logic clock, and digital interfaces. The PLA is programmed to provide the serial bit stream as bi-phase and non-return to zero (NRZ) digital. These two formats cover a wide range of communications systems including fiber optic, hardwire, and radio frequency (RF).

The system has a bit rate of 2400 bps, but the bit rate can be increased easily. A practical limit to this FM system is approximately 30,000 bps. However, if the signal coupling at the surface continues to be strong and noise-immune, the bi-phase output could drive the coaxial system directly. The bi-phase data rate exceeds 100,000 bps. Data rates that high are approaching imaged data requirements.

Another important attribute of adaptability is to provide different supply voltages for different sensors. Only battery power (32V) is supplied on the coaxial cable. Once received, this voltage is converted to four different voltages: +12V, -12V, +5V, and -5V. A DC-to-DC converter generates these different voltages. The converter increases battery life by reducing current drain from the batteries and allowing the battery voltage to range from 18V to 32V without affecting sensor electronics. A second DC-to-DC converter generates the 1,300V GRS bias voltage. Current requirement for the downhole electronics is only 60 mA at 30V.

Downhole Components

Downhole components of the gamma ray detection sensor system consist of a GRS, MCA, a 1300V power supply, orientation sensors, a signal conditioning and transmitter board, and a coil containing coaxial cable for transmitting data to the surface. The downhole components are contained within O-ring sealed stainless steel tubes to protect them from the drilling environment. The GRS detector was placed forward, toward the drill bit. The coil is in the rear to accommodate communication back to the surface.

Applied Physics Systems built the orientation sensor package. This microprocessor-controlled system utilized a three-axis fluxgate magnetometer for azimuth and three axis accelerometers for inclination. The microprocessor uses the magnetometer and accelerometers for calculation of role, pitch, and heading.

The EMWD telemetry board is set up to read orientation values from the PLA every 1.5 seconds. These data are then transmitted to the surface and stored with other measurement data vis-à-vis time on a field personal computer (PC). Data coming from the PLA is already in the final form--heading, pitch, and role. The PLA microprocessor also provides the calculated values for magnetic and gravitational fields. These two additional calculated values provide the system with some measure of data quality. Valid accelerometer and magnetometer readings always provide constant values for magnetic and gravitational fields. When these values are not valid, primarily due to drilling rotation, the heading, pitch and role readings are ignored. By taking orientation readings every 1.5 seconds, a large number of readings are acquired whether the drilling is progressing or stopped for any reason; i.e. adding additional drill rods and/or making a change in steering trajectory. The most accurate readings are acquired when drilling is paused.

The specifications for the components included in the EMWD system as used in the demonstrations are shown in Table 1.

Table 1. Specifications of EMWD GRS System	
Transmission Data Rate	2,400 Baud, 7 analog and 2 digital channels
Battery Pack	32V, approximately 20 hours of continuous operation
Multi-Channel Analyzer	256 Channels 0.15 to 1.6 MeV range Complete spectrum every 20 seconds
Gamma Detector High Voltage Supply	2 x 4-inch sodium iodide crystal with matching PMT 24V step up to 900-1,600V for PMT biasing
Angular Orientation Sensor	±0.5 degrees inclination ±1.0 degrees azimuth Complete set of orientation readings every 1.5 seconds

Uphole Components

The uphole system consists of a battery pack/coil, pickup coil, receiver, and a PC. During drilling, the system monitors: (1) gamma radiation by gamma ray spectrometry, (2) pitch, role and azimuth using the orientation sensors, (3) the +12V and -12V required at the downhole signal conditioning and transmitter board, (4) the uphole battery voltage as measured downhole, and (5) two temperatures associated with the detector and instrumentation.

Cable Deployment System

The cable is contained in a spool located with the downhole components of the system. The cable from the downhole instrument package is pulled through each piece of drill pipe and through the drill head to the battery pack/coil mounted on a spindle at the rear of the drill head and is connected to the uphole components. The coaxial cable is pulled through each section of drill pipe and the drill head using fish tape. The spindle leads to the drill fluid handling system. Drill fluid pressure is normally in the range of 300 psi (1.435 kPa) to 500 psi (2.392 kPa), but can go as high as 1,500 psi (7.177 kPa). A cord grip fitting is used to seal against the 0.07-inch (1.8-mm) outside diameter coaxial cable. The sealing grommet in the cord grip fitting is slit so that it can be removed from the cable, allowing the connector to pass through the body of the cord grip fitting. This arrangement has been tested to 600-psi (2.871-kPa) air, which is approximately equivalent to 3,000-psi (14.354-kPa) water, without leakage.

Data Transmission Surety

Since human safety is a primary consideration, reliability and high data surety are priority system requirements. To meet these requirements, the system design incorporates data quality verification techniques to ensure data reliability. The basic format used in the EMWD system is also used in the weapons complex for very high data surety where destructive testing may cost hundreds of millions of dollars and getting “one shot” reliable data is imperative.

Data Collection System

The data collection system is comprised of a computer, stationary magnetic pick-up coil and receiver, battery pack and rotating magnetic coil, and the downhole electronics package. The coils couple the FM signal between the rotating drill pipe/rotating magnetic coil and the stationary magnetic pick-up coil and receiver, which are mounted on the drilling platform. The receiver converts the FM signal into a serial bit stream. A computer equipped with a telemetry serial card receives the data and displays downhole measurements in real time.

The EMWD system provides real-time data on as many as eight differential/single analog multiplexers and any number of digital channels. The sampling speed from the analog channels can reach 100 kHz. For the EMWD system, three digital channels are used. Readings are taken at a rate of 20 per second. The telemetry system is programmable firmware that can easily support many different data formats and additional data channels. The current format (digital FM bi-phase, 4800 baud) provides excellent noise rejection. An SNL-designed receiver removes FM carrier noise, generates data clock, and buffers data for use by an IBM or compatible PC. A battery pack can supply downhole instrumentation power for more than 20 hours of drilling. A DC-to-DC converter increases battery life by reducing battery current drain and allowing the battery voltage to range from 18V to 32V without affecting sensor electronics and data quality. The battery pack remains topside for easy maintenance.

Data transmission is digital FM in a bi-phase format. Digital FM electrical data transmission is presently state-of-the-art for electrical data transmission and provides a very high signal-to-noise ratio. Bi-phase is a technical term used in the telemetry industry that simply means each digital datum is a transition, not a level. In most digital systems, a "one" logic bit is sent as a 5V level and a "zero" logic bit is a 0V level. In this system, bits are transmitted by the PHASE of a clock, thus the term bi-phase. Logic bit "one" is transmitted as one phase of the clock and logic bit "zero" as the other. The clock phase signal is easily transmitted as a wireless data stream at constant frequency. This creates a serial bit stream that is proactive. Bi-phase data transmission is commonly used in satellite data transmission because it is self-clocking.

Self-clocking data benefits bi-phase data transmission. In simple digital data transmission, a series of zero logic bits creates a static condition where no signal is received. If the data series is very long, then the receiver can confuse a period of 12 zeros with 11 zeros or 13 zeros. In the worst case, a transmission system can fail and the receiver believes the data stream consists of all zero logic bit levels. By clocking the data in a bi-phase form, the proper operation of the timing circuits is validated. A possible failure mode for any system making a rate measurement verses time can be caused by the crystal-based timer oscillating at a harmonic. For example, a 5 MHz timing clock can run at 10 MHz. Because time is relative, a system running at twice the expected clock speed means the gamma rate calculation is halved. This fault could prevent the operator from seeing a dangerous condition. To detect clock error, the bi-phase data are tied to the clock such that any error in the timing clock is measured in the data transition rate at the surface. This validates proper operation of the instrumentation clock at all times.

For these tests, a simple bit stream comprised of all the basic elements was used. The bit stream uses a sync-word (sixteen unique bits repeated for each frame of data). The computer receives the bit stream and qualifies the incoming data for data rate, proper number of bits, and the correct sync-word. If any of these elements are incorrect, the data sync indicator changes from green to red and the data display halts. The minimum word size is sixteen bits where the upper four bits are dedicated to word count (data position in the bit stream) and parity. Naturally, the number of data channels (i.e., gamma or temperature) is unlimited for any practical purpose.

Drilling Platform

The EMWD system can be adapted for use with most drilling platforms. A & L Underground supplied the drilling platform used for the Hanford demonstration. This system uses a Tensor Steering Tool System with TruTracker™ Guidance System to measure drill bit location and depth.

System Operation

Preliminary field tests were completed at SNL, at the radioactive calibration facility in Grants, New Mexico, and at the Charles Machine Works, Inc. (CMW) Directional Drilling Range in Perry, Oklahoma. The EMWD with the GRS sensor system was demonstrated in the field in April 1996 at the Savannah River Site (SRS) in the F-Area Retention Basin. Phase I of the demonstration determined the radiological background. Phase II was a "hot site" demonstration that continuously monitored for gamma activity in real time while drilling two boreholes. Contaminant levels of cesium-137 recorded by the EMWD during drilling agree with the contaminant levels previously determined through quantitative off-site laboratory analysis of the soil samples. In addition, previously unidentified gammas radiation “hot spots” were identified. The successful demonstration resulted in no radiation-contaminated equipment or waste.

The EMWD was tested with the orientation package at the CMW Perry "cold site." No problems were experienced in taking the orientation sensor package data along with the gamma spectrometer data and correlating the two sets of data. The demonstration at Hanford included drilling one directional borehole each at the Mock Tank Leak Simulation Site and the Drilling Technology Test Site. The technology demonstration consisted of the development of one borehole under a mock waste tank at a depth of approximately 27 feet following a predetermined drill path, tracking the drill path to within a radius of 5 feet, and monitoring for zones of radiological activity using the EMWD system. The purpose of the second borehole was to demonstrate the capability of drilling to a depth of 70 feet, the depth needed to obtain access under the Hanford waste tanks, and continue drilling horizontally. The EMWD system tracked the drill bit location to within 2 feet of the reference provided by a commercial tracking system. The primary purpose of the Hanford demonstrations was to show that EMWD could be deployed into the difficult media, such as soils strewn with large cobbles, present at the Hanford Reservation at the required depths. Since neither the Mock Tank Leak Simulation Site nor the Drilling Technology Test Site have any contamination, only natural gamma emitters such as potassium-40 (K-40) were measured.

SECTION 3
PERFORMANCE

Demonstration Plan

Savannah River Site

During April 1996 a demonstration was conducted at the Savannah River Site (SRS) F-Area Retention Basin (FRB). The demonstration provided EMWD system performance data under field conditions at a previously characterized "hot" site. Demonstration participants included SNL, Westinghouse Savannah River Company (WSRC), and DOE-Savannah River and DOE-Albuquerque.

The FRB (dashed rectangle in Figure 3) is approximately 61 m (200 ft.) long, 36.5 m (125 ft.) wide, and 2 m (7 ft.) deep, and has a total volume capacity of approximately 4,685 m^3 (175,000 ^{3}ft.). This basin was constructed as an unlined, temporary container for potentially contaminated cooling water from the chemical separation process and storm sewer drainage from the F-Area Tank Farm. When contamination was detected in cooling water, the water was diverted to the retention basin or F-Area seepage basins. Additional contamination of this basin came from various spills or overflows at the basin. The basin was in active use from 1955 until 1972, when a lined retention basin replaced it. In 1978 the FRB was excavated, backfilled with soil, and covered with grass. Backfill in the basin extends to a depth of approximately 3 m (10 ft.). The site was evaluated through soil sampling in early 1979; the locations of sample holes and boreholes are shown in Figure 3. The major gamma-emitting radionuclides present are strontium (Sr-89/90) and cesium (Cs-137).

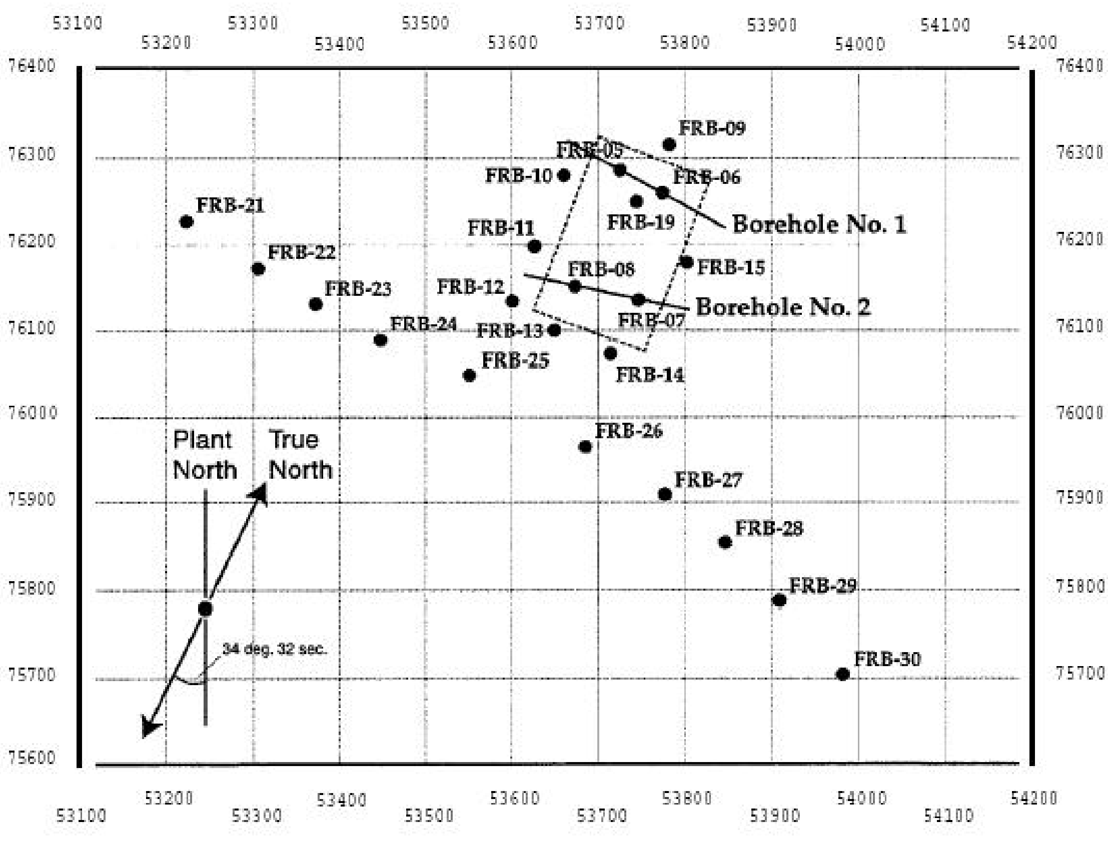

Figure 3. Locations of Vertical Sample Holes and Horizontal Boreholes in and around the Savannah River Site (SRS) F-Area Retention Basin (FRB) Demonstration Site (dashed rectangle). (The vertical sample holes coded FRB 21 through FRB 30 were looking for leaks along a pipeline and were not part of this demonstration.)

Phase I of the demonstration at the FRB determined the background radiation conditions for the site as seen by the EMWD. Background conditions were determined by drilling one angled borehole to a depth of –5 m (-17 ft.) at an adjacent radiologically "clean" site. The data on the background conditions were used in Phase II of the demonstration.

Phase II of the EMWD system demonstration consisted of measuring environmental conditions in real-time while drilling two horizontal boreholes. Borehole No. 1 passed very close to sample locations FRB-05 and 06, and came nearest to FRB-19; Borehole No. 2 passed very close to sample locations 07 and 08 (see Figure 3). These sample locations had known contamination values.

Under normal conditions, 3-7 spectra were obtained for each 3 m (10 ft.) length of drill rod. At the points of closest approach to FRB-05, -06, 07, and 08, the drilling operation was stopped so additional spectra could be gathered from these areas before drilling continued. At the discretion of the scientific team, drilling was halted at other points of interest, and spectra were accumulated. The concentration data for each drill rod was adjusted by subtracting measured background as determined during Phase I and shown evenly distributed along that drill rod.

Hanford Reservation

The Tank Waste Remediation System (TWRS) at the Hanford Reservation has a series of locations that are known to be contaminated by tank wastes. A demonstration of EMWD was conducted to assess the capability of horizontal directional drilling (HDD) to follow a predetermined drill plan in a simulated tank farm environment and define zones of subsurface radiological contamination using the EMWD system.

The Mock Tank Simulation Site (MTLSS) is located in a part of the 200 East Area of the Hanford Reservation. This area is underlain by a slightly consolidated, generally uncemented, interstratified gravel, sand, and silt. The dominant lithology encountered while drilling at the MTLSS was medium- to coarse-grained sand and granules, occasional pebbles, and silt-rich intervals. All drilling activity occurred within the vadose zone. No contamination was known to be present, but sufficient differences in the gamma activity of naturally occurring K-40 across the soil facies were anticipated to allow testing of the EMWD.

The mock tank consists of a 15-m (50-ft.) diameter steel ring to simulate a tank with its base recessed approximately 1.5 m (5 ft.) below the ground surface. While smaller than a typical 25-m (75-ft.) diameter single-shell tank (SST), the surface interferences, while not including a full suite of ancillary piping, are similar to those anticipated to be present around a full-size SST. This is a cold test site originally designed to conduct Electrical Resistance Tomography studies.

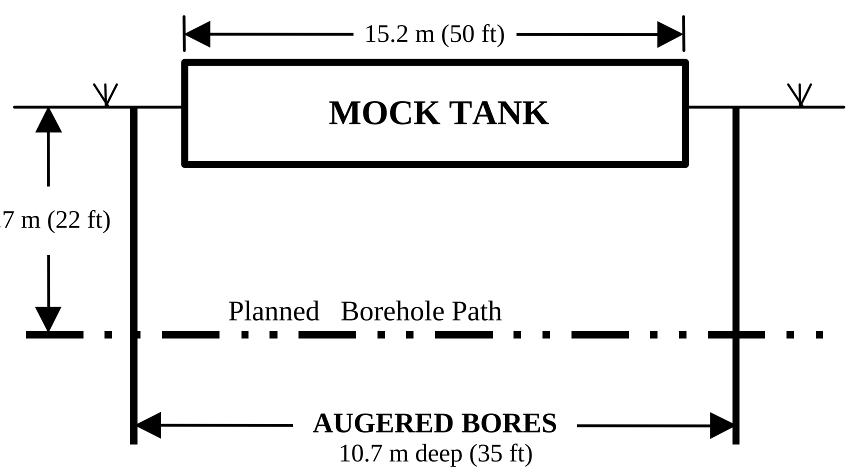

Figure 4. Plan View of the Mock Tank Leak Simulation Site (MTLSS)

The second drill site for this demonstration was the Drilling Technology Test Site (DTTS) located immediately north of the 200 Area Fire Station in the Environmental Restoration Disposal Facility (ERDF) map area. This site has been used for a variety of drilling demonstrations. Some of the sand and gravel units are totally unconsolidated and had presented some difficulty to controlling the drill bit during a previous test of directional drilling. The geology of the DTTS is coarser and more varied than that of the MTLSS, and thereby provided an environment to test the deployment of EMWD with existing HDD technology in media representative of most SST farms at Hanford. While drilling, interbedded sand, silt, and gravel with a range of induration (cementation) were encountered. Gravel units near the surface (down to approximately -6 m (-20 ft.) are unconsolidated and coarse to very coarse with cobbles ranging to more than 0.250 m in diameter. The water table was anticipated to be at approximately -70 m (-235 ft.) below the surface, but was not encountered. Therefore, all drilling activity occurred within the vadose zone. No contamination was known to be present, but sufficient differences in the gamma activity of naturally occurring K-40 across the facies were anticipated to allow testing of the GRS.

The second borehole was drilled at the DTTS using a mud motor to penetrate through about 6 vertical meters (about 20 ft.) of boulders/cobbles; the remainder of the hole was drilled with a rotary jet. The purpose of this test was to demonstrate the capability of drilling to a depth of about -21 m (-70 ft.), the depth required to drill under a Hanford SST. The borehole was drilled at an angle of 16°, reached a depth of about -23 m (about -75 ft.), and went horizontal for approximately 18.3 m (60 ft.).

The EMWD system tracked the position of the drill bit and measured the naturally occurring radiation while both boreholes were drilled.

Results

Savannah River Site

A comparison of the physical conditions for the two methods was required to make a valid comparison between the EMWD results and the laboratory analysis of soil samples. The soil samples were obtained using a split-spoon soil sampler. This device was used to collect 7.6-cm diameter by 61-cm long soil samples at 61-cm intervals. The results for Cs-137 were for an average of the entire sample, and thus had a location uncertainty of ±30 cm. With this soil sampling system, only contamination captured within the 7.6-cm diameter sample contributed to the results. With EMWD the spectrometer used in the GRS system collected data from an approximately spherical volume surrounding the sodium iodide (NaI) crystal. The part of the “sphere” along the drill string did not contribute to the signal. The radius around the NaI crystal from which data were obtained was a function of the soil and the energy of the gamma ray being studied. Since the EMWD does not have a directional window, the Cs-137 distribution around the sensor is unknown.

The drill bit location was obtained using the high-frequency electromagnetic beacon with the walkover monitor. The spectral data were successfully obtained using the EMWD GRS. The gamma radiation levels recorded by the EMWD system (see Figure 5) were compared to those previously determined by quantitative laboratory analysis of soil samples collected at those locations. For this comparison, the raw data were converted to pCi/g as shown in Figure 6. The results showed general agreement between the laboratory analysis of soil samples and EMWD results for Cs-137. EMWD identified areas of Cs-137 contamination not previously identified by the soil sampling process. These are shown in Figures 7a and 7b for Boreholes #1 and #2, respectively. In addition, the soil volume examined for Cs-137 by EMWD was much greater than that studied by conventional soil sampling. The results are presented in detail in the final report (SAND97-2028) Lockwood, Norman, and Williams, 1997.

The pullback was also successful. Due to the possibility of contamination, the crew dressed out in full protective clothing for the pullback. The soil on the drill rod was contained in the trench that was both the entry and exit point for the demonstration. The Ditch Witch crew used a drill rod wiper, an instrument they engineered, to remove most of the soil; and then they used paper to wipe the rods clean. The radiation control officer checked for contamination on the drill rods using a gamma detector, a beta/gamma detector, and swipes from each drill rod and other critical areas in the trench. All results were negative. The pullback operation successfully concluded with contaminated soil contained in the trench and drill rods completely decontaminated.

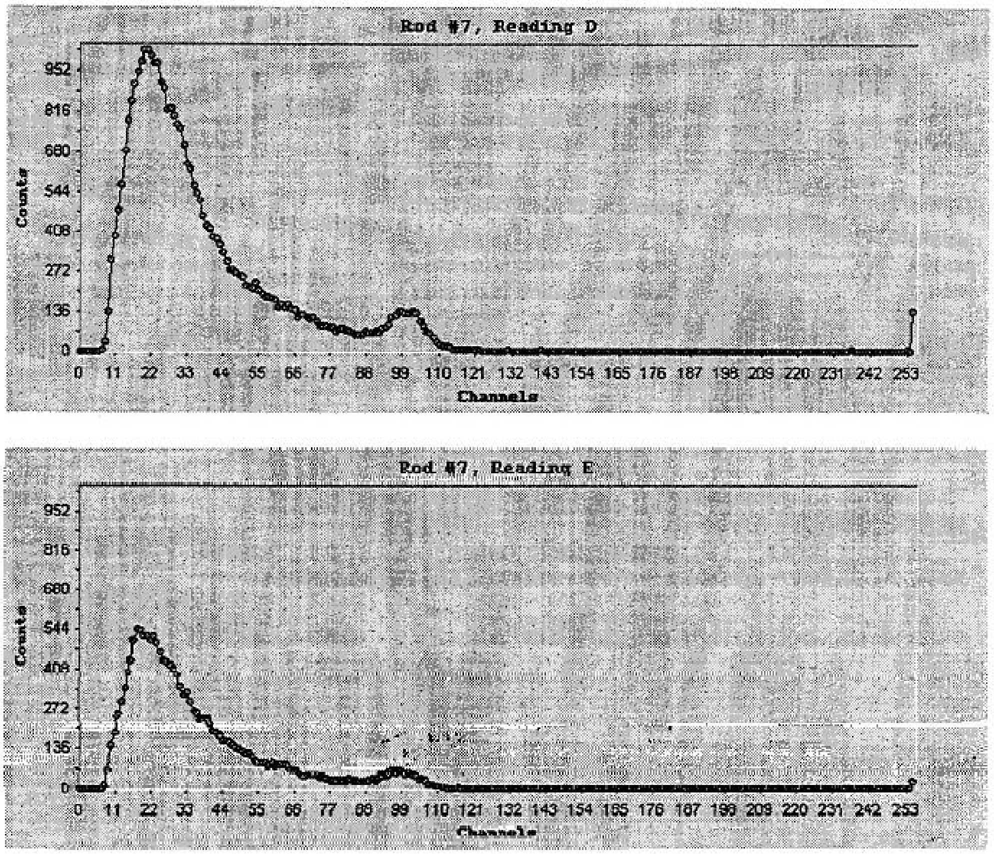

Figure 5. Examples of raw data obtained with the EMWD gamma-ray spectrometer at the Savannah River Site (SRS) F-Area Retention Basin while drilling horizontally in a "hot" region. (Lockwood, Norman, and Williams, 1997)

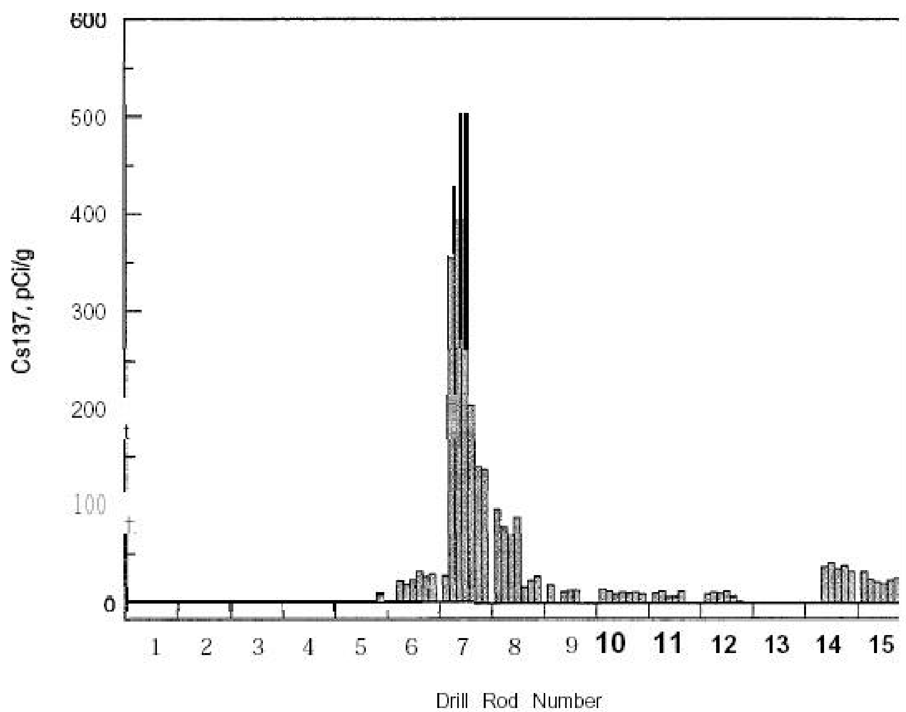

Figure 6. Example of Cesium Concentration Obtained with the EMWD gamma-ray spectrometer system at the Savannah River Site (SRS) F-Area Retention Basin. (Lockwood, Norman, and Williams, 1997)

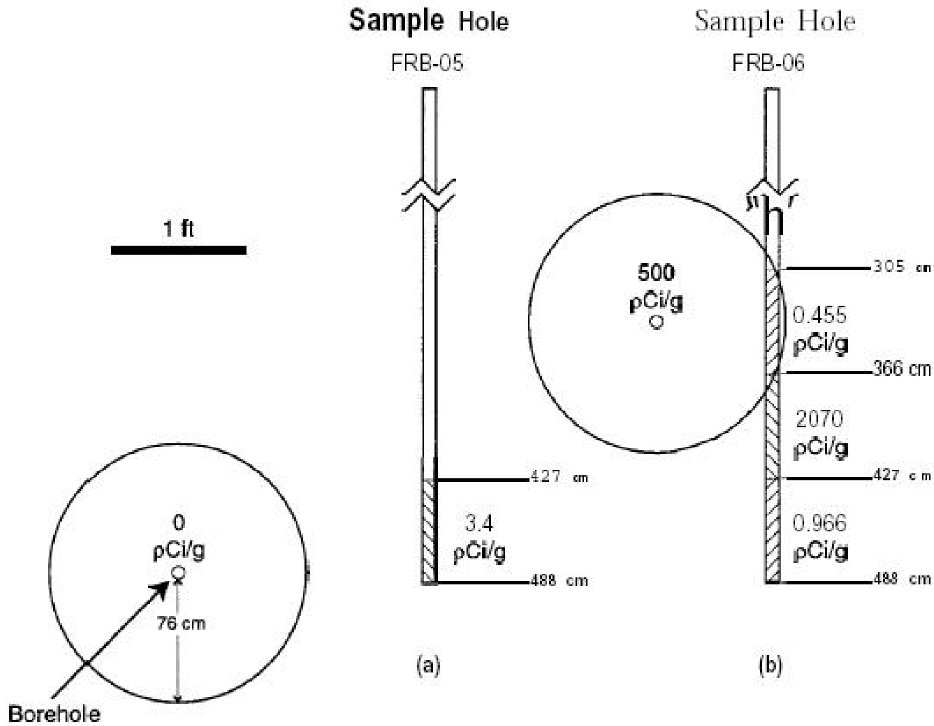

Figure 7a. This is a vertical cross section of Borehole #1 through sample hole and the EMWD GRS at the distance of closest approach.

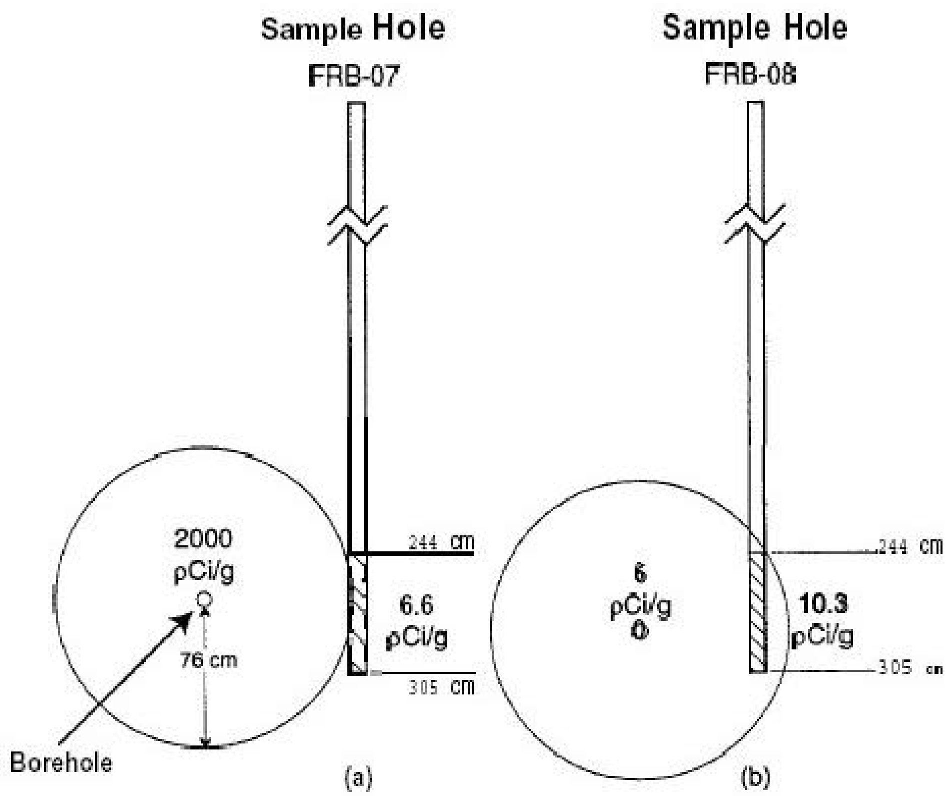

Figure 7b. This is a vertical cross section of Borehole #2 through sample hole and the EMWD GRS at the distance of closest approach.

Hanford Reservation

The EMWD tracking survey, the Tensor Steering Tool survey, and the TruTracker™ survey at the MTLSS indicated average maximum depths of approximately 7.5 m (25 ft.), 8.1 m (27 ft.), and 7.3 m (24 ft.), respectively, for this horizontal run. The absolute deviation between the EMWD tracking survey and the tensor survey was 0.64 m (2.1 ft.) or less; between the EMWD system and the TruTracker™ survey, the absolute deviation was 1 m (3.4 ft.). The absolute deviation between the Tensor Steering Tool and the TruTracker™ surveys was 1 m (3.4 ft.). The drill bit position was known within a sphere having a radius of no greater than 1 m (3.4 ft.) and a known direction relative to the prescribed baseline at all times. The agreement between the EMWD survey and the Tensor Steering Tool and TruTracker™ surveys indicated that borehole reentry was successful. The EMWD was fully operational and background gamma was recorded continuously while drilling.

Drilling the first borehole in the Hanford lithology using the Tensor Steering Tool and TruTracker™ systems was initially difficult (Figure 8). However, upon re-entry with the EMWD system drilling was significantly easier. This is an indication that the drill bit followed the same path upon reentry of the borehole. The bit location measurements from the Tensor Steering Tool, TruTracker™, and SNL tools are directly comparable for depth. All depth readings were easily within the required $\pm$ 1.5 m (5 ft.) window of each other. The EMWD tool initially took readings every 3 m (10 ft.). This was done to increase accuracy while drilling the initial bend radius. Once the drilling progressed horizontally this error normally was less of a concern. The EMWD tool quickly made orientation measurements whenever the tool was stopped for a few seconds.

The planned drilling profile was for a straight line heading along 226.7° (where 360° is North and 270° is heading West). The TruTracker™ left-right measurement was used during drilling to keep the drill bit on the planned heading. Upon completion of the drilling, the Tensor Steering Tool left-right measurement was calculated. Here again, the measurements were within $\pm$ 1.5 m (5 ft.). For left-right measurements, the TruTracker™ measurement is the more accurate than the Tensor Steering Tool orientation left-right measurement. A typical plot of naturally occurring gamma radiation is shown in Figure 9. The results are presented in detail in the final report (SAND99-1479) Williams et al., 1999.

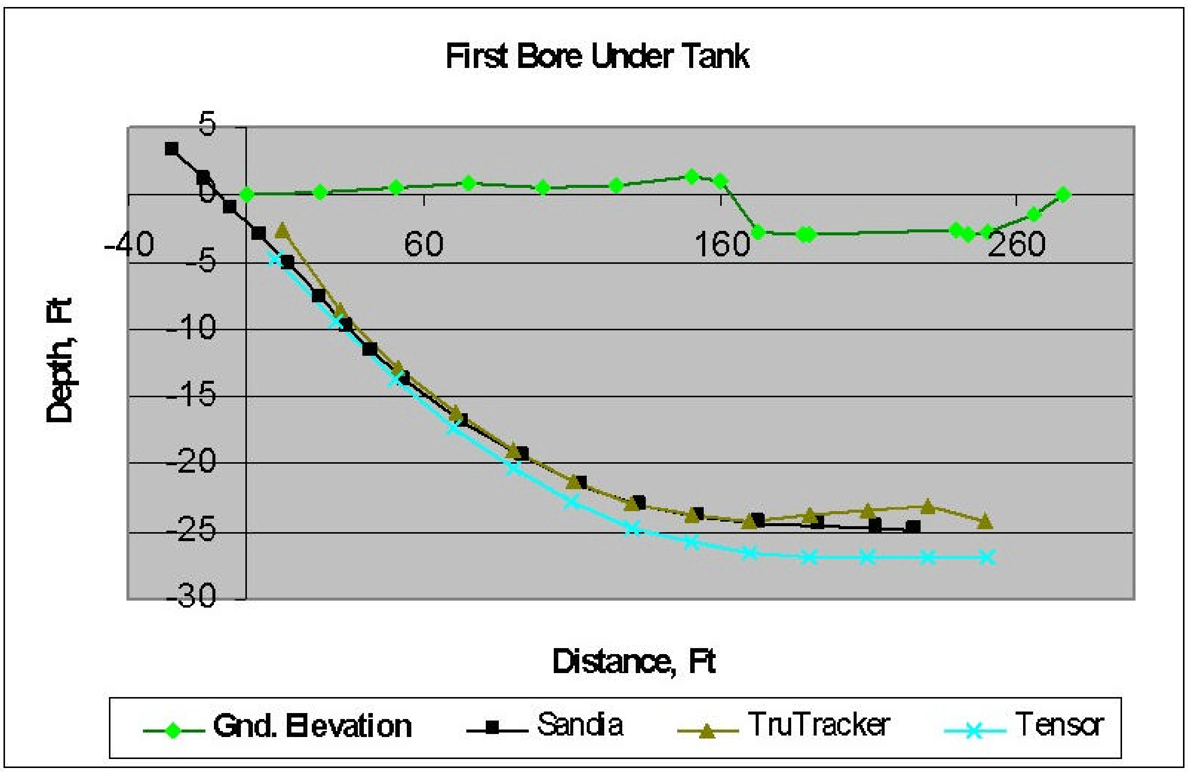

Figure 8. Mock Tank Leak Simulation Site (MTLSS) borehole depth plot showing calculated depth profiles from the EMWD, Tensor Steering Tool, and TruTracker™ . The mock tank at the Hanford Reservation was inside the surface ground depression. (Williams et al. 1999)

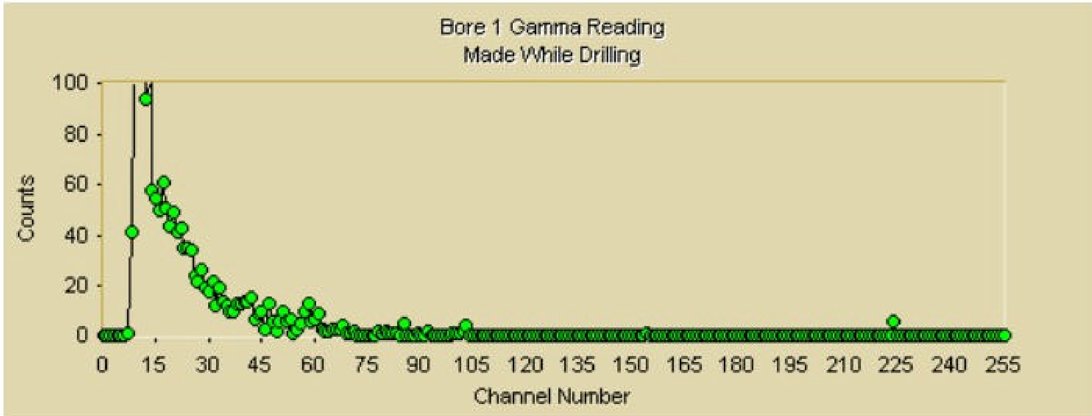

Figure 9. This is a typical EMWD gamma spectrometer reading taken at the Hanford Reservation during horizontal drilling at the Mock Tank Leak Simulation Site (MTLSS). Naturally occurring potassium-40 is the primary gamma emitter and, under ideal conditions, its gamma radiation should show up in channels 175 to 195.

At the DTTS, the target depth was approximately -23 m (-75 ft.), resulting in a bore of approximately 122 m (400 ft.). The EMWD and TruTracker™ systems agreed on bit location (Figure 10). The borehole was re-entered to run the EMWD tool in the stainless steel housing out to a length of 61 m (200 ft.). As in the first drill, three independent depth readings were in very close agreement and well within the required $\pm$1.5 m (5 ft.) window. To demonstrate the capability to push casing in the difficult Hanford lithology of the DTTS, 18.3 m (60 ft.) of casing were emplaced at this site. An attempt to take a sample from this borehole using a small sampler was unsuccessful; the sampler was not designed for the cobble/boulder environment at Hanford. The EMWD was fully operational and measured and recorded the natural background gamma radiation such as K-40 (Figure 11). The results are presented in detail in the final report (SAND99-1479) Williams et al., 1999.

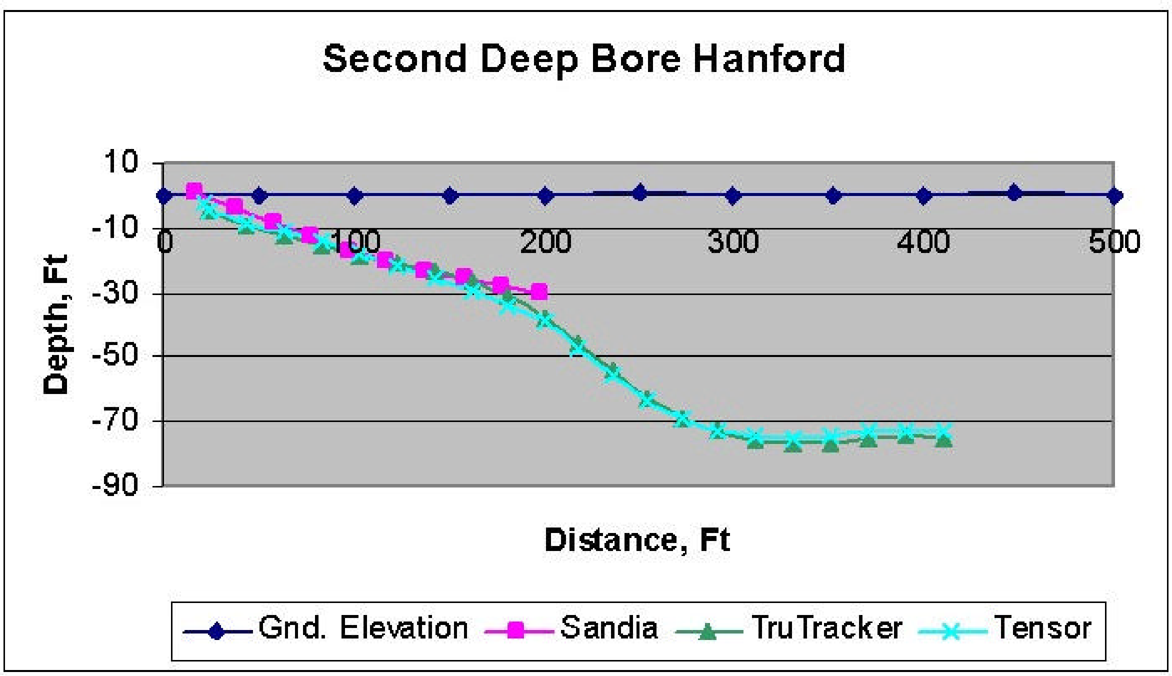

Figure 10. This is an example of horizontal depth readings at the Drilling Technology Test Site (DTTS) on the Hanford Reservation.

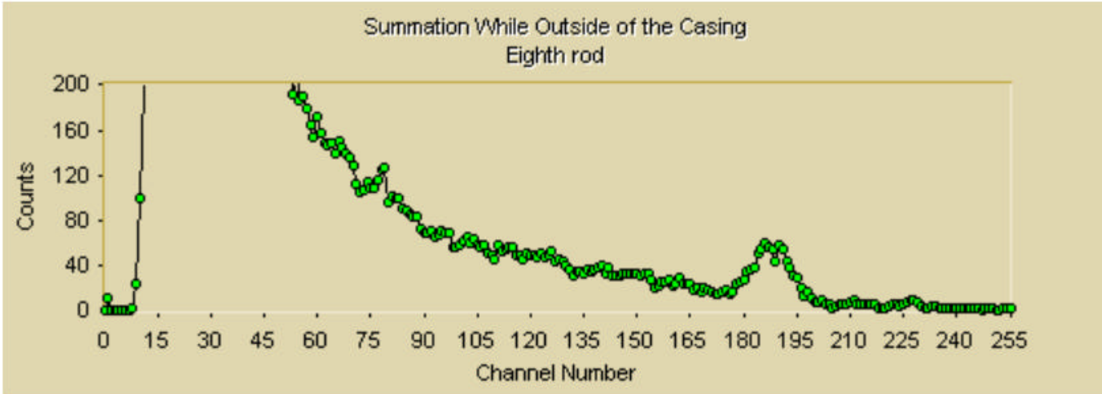

Figure 11. This is a summation (3.84 minutes) of spectra while outside the casing at the Drilling Technology Test Site (DTTS) on the Hanford Reservation. Note elevated counts in channel 175-195 that are probably due to potassium-40.

Conclusion

The EMWD demonstrations at SRS and Hanford were successful at tracking drill bit location during horizontal drilling. The measurement of the spectra of gamma-emitting radionuclides, whether from known contaminants or naturally occurring radionuclides, was also demonstrated.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

Baseline Technology

The baseline method for measuring radionuclides in contaminated soils requires the collection of samples that must be transported to a laboratory and analyzed with standard nuclear industry counting techniques. The advantage of the baseline approach is that it provides a high degree of precision and accuracy at those locations from which samples were obtained; however, it is extremely costly and presents numerous risks and time delays associated with the collection, transport, and analysis of radioactive samples.

Since the distribution of contamination is not homogenous at most waste sites, a large number of samples is typically required to accurately characterize and map the extent of contamination. Some of the samples may not contain radioactive or other contaminants readily detectable in the field. Due to the high cost per sample for the baseline technology, budgetary constraints will limit the number of samples collected and analyzed. This may result in inadequate site characterization and lead to the design of inefficient or ineffective remedial systems.

The baseline technology is also constrained by obtaining subsurface samples in bored or direct push holes around the periphery of the contaminant source. This sampling approach is inadequate to properly characterize the area beneath a potential contaminant source. It may be environmentally unacceptable and hazardous to bore or push through the contaminant source to sample soils beneath it, thus compromising the integrity of any installed safeguards and creating safety hazards for site personnel from investigation-derived waste (IDW).

Other Competing Technologies

No other technologies are currently available that can be used for *in situ* measurement and identification of radionuclides underneath large structures, waste storage tanks, landfills, and other contaminant sources. In addition, no other technology is currently available that can accurately track the location of the drill bit beneath contaminant sources and correlate location and measurement data in real time.

Technology Applicability

EMWD technology can be used to characterize underground radioactive contamination and other attributes anywhere the subsurface is conducive to angle, horizontal, or vertical drilling. The number of parameters that can be sensed downhole is dependent on the kind of sensors integrated into the system. For the present demonstrations, the GRS was the primary sensor technology. The GRS sensor used a NaI scintillation crystal, which has relatively high detection efficiency but has relatively poor energy resolution. Higher resolution detectors may be needed for applications where a higher signal-to-noise ratio is necessary to separate closely spaced gamma peaks. Additional sensors can also be integrated into the EMWD system.

Patents/Commercialization/Sponsor

EMWD was developed under U.S. Department of Energy funding by Sandia National Laboratories using a blend of commercially available technologies and contractor support. Patent No. 5,722,488 covers the coaxial cable coil. There are no commercial sponsors.

SECTION 5
COST

Methodology

Introduction

EMWD is an enabling technology. It enables measuring, identifying, and fixing the underground location of gamma emitters underneath contaminant sources while drilling. It can minimize safety hazards and eliminate the costs and delays attendant to soil sample collection, shipping and handling, and off-site laboratory analysis. The data collected by EMWD can also be used to optimize a sampling strategy or identify optimum sample collection locations in real-time during the sampling process.

HDD rigs can bore underneath contaminant sources without compromising their integrity. EMWD is an add-on technology that allows HDD to return location and environmental information to the surface for use by the on-site characterization team. The more common baseline technology, boring vertical holes to collect samples, cannot be used when adverse or potentially adverse environmental effects could result, such as drilling through buried waste or into high-level radioactive waste tanks. HDD without EMWD can also be considered a baseline technology that can be used to “blindly” collect soil samples underneath a contaminant source without real-time feedback.

For this cost analysis, HDD without EMWD will be used as the baseline technology. Consequently, characterization of the subsurface beneath the contaminant source would require the collection of soil samples. The samples collected would be screened for contamination with field instruments, packaged, documented, and shipped off-site to a commercial laboratory for analysis.

Methodology

The hypothetical cost comparison site is a large building with drain lines beneath its foundation that are suspected of leaking gamma-emitting radionuclides, primarily Cs-137, into the soil below. The building is 80 m long and 40 m wide. The target horizontal horizon is 2 m below the building. The location of the two drain lines is known and two horizontal holes are drilled directly under both lines. The drain lines run the entire length of the building. The rate of drilling progress is 40 m per 8-hour day, and setup at each drill site takes 4 hours. Soil samples are collected at 1-m intervals using the baseline approach, and continuous gamma spectrometer data are collected using the EMWD approach.

Cost Analysis

The cost of the baseline approach was significantly higher than the EMWD approach in this situation. The cost difference can largely be attributed to the need to take samples and send them out for laboratory analysis. The sampling requirement increased expenses by over 150%. If more frequent sampling intervals were required, the cost difference would be even greater. Tables 2 and 3 detail the cost of carrying out the methodology for the baseline and EMWD technologies.

The cost differences can vary substantially depending on the site characterization requirements. In situations where a vertical drilling or direct push approach can be used as the baseline, HDD is generally more expensive because the horizontal holes take longer to drill and cover more ground than the vertical holes. This is especially the case where both approaches must access all locations in a comprehensive grid at one or more levels in the subsurface. In the opposite kind of situation, where a flexible approach can be used to locate and define subsurface contamination, EMWD can save considerable exploratory costs by allowing field personnel to guide the drill bit on the basis of the real-time data being collected. Finally, there are situations where EMWD cannot, or may be too costly to use, with HDD due to nature of underground conditions.

Table 2. Approximate Costs of Baseline HDD Sampling and Analysis[1,2]	
Drilling Crew & Equipment Rate ($300/hour X 60 hours)	$18,000
Consumables ($15/soil sample X 160 samples)	$2,400
Hollow stem auger drilling (Unit cost $10/foot X 525 feet)	$5,250
Split Spoon Sampling (Unit cost $20/foot X 525 feet)	$10,500
Disposal of Drill Cuttings ($250/drum X 5 drums)	$1,250
Disposal of Decontamination Fluids ($225/drum X 10 drums)	$2,250
Decontamination Labor ($75/hour X 8 hours)	$600
Per-Diem for 2 Person Crew ($72/day X 8 days)	$576
Technical Staff ($75/hour X 64 hours)	$4,800
Health Physicist Oversight ($100/hour X 64 hours)	$6,400
G&A Overhead (10%)	$1,120
Gamma Spec. Sample Analysis @ Laboratory ($150/sample X 160 samples)	$24,000
Sample Handling and Shipping ($25 average cost X 160 samples)	$4,000
Total Estimated Cost	$81,146

Table 3. Approximate Costs of Operating EMWD HDD GRS System[1]	
Drilling Rig, Crew, & Equipment ($300/hour X 40 hours)	$12,000
Hollow stem auger drilling (Unit cost $10/foot X 525 feet)	$5,250
EMWD Consumables	$2,500
Per Diem for 3 Person EMWD Crew ($108/day X 5 days)	$540
Technical Staff (2) ($150/hour X 40 hours)	$6,000
Health Physicist Oversight ($100/hour X 40 hours)	$4,000
G&A Overhead (10%)	$1,000
Total Estimated Cost	$31,290

[1] Drilling, sampling, decontamination, disposal, analysis, and other costs are estimates made by comparing various cost data sources.
[2] The cost analysis presented in Table 2 does not include the costs resulting from the time lapse (generally at least 2-4 weeks) between sample collection and the analysis results are received.

The cost of building an EMWD system includes custom engineering, software development, and the purchase of commercially available components and equipment. The following are general cost estimates for the following items:

Table 4. Approximate Cost of Building EMWD GRS System	
2 x 4-inch Sodium Iodide Detector with matching Photo-Multiplier Tube	$7,000
Angular Orientation Sensor (±0.5 degrees inclination, ±1.0 degrees azimuth)	$1,000
Nonmagnetic Housing	$10,000
Instrument Housings	$2,000
High Voltage Supply (24V step up to 900-1600V for Photo-Multiplier Tube biasing)	$700
Battery Pack/Magnetic Coils/Magnetic Pick Up and Receiver	$1,500
Cable/Cable Deployment/Retrieval System	$2,000
Downhole Electronics	$5,000
Uphole Electronics	$5,000
Data Collection System	$3,500
Software/Programming	$7,300
Engineering/Custom Machining	$5,000
Total Estimated Cost	$50,000

Replacing consumables and maintaining the EMWD system is expected to average about $2,500 per deployment. Other components of the EMWD system are expected to survive many deployments without the need for major maintenance or updating.

Cost Conclusions

The cost of building an EMWD system is relatively small and the cost can be amortized over many years and many site characterizations. The cost of consumables is minor.

It is much more economical to use EMWD with HDD to characterize the subsurface beneath contaminant sources than the baseline HDD sampling and laboratory analysis approach. In the event vertical drilling or direct push technologies can be used as the baseline, the cost advantage shifts to the baseline technology. However, the continuous spectral gamma data collected by EMWD with HDD provides a more comprehensive picture of the gamma emitters in the subsurface soil horizons accessed.

SECTION 6
OCCUPATIONAL SAFETY AND HEALTH

Required Safety and Health Measures

Safe Working Practices

Safety in all operations at the any DOE site is of the utmost importance. Stringent criteria should be in place as a contractor pre-qualification requirement. Safe working practices should be strictly enforced and a safety consciousness established with the drilling subcontractor and its crews. Before operations begin, the drilling contractor should institute a safety education program for selected drilling personnel that includes classroom training and practical experience. During operations, all personnel involved in the operations must follow the safety plan. Lack of safe working practices in any environment, especially at high-level waste tank farms, is unacceptable.

Site Setup

The operations site should be ready for the arrival of the EMWD team. All necessary surveys, equipment, power, water, sanitary facilities, etc., should be identified prior to the initiation of operations. A pre-operational radiological survey of equipment should be conducted prior to mobilization to the site.

Equipment

The drilling subcontractor's equipment should be thoroughly inspected prior to arrival on site. This inspection should include equipment guards, walkway railings, stairways, overhead machinery, and any other areas that could result in injuries. All hoses should be inspected and faulty hoses replaced prior to mobilization to the site. The equipment should be thoroughly cleaned of all soils and contaminants (such as oils, fuel, and grease), and all leaks repaired. Only tools and equipment required to accomplish the job should be allowed onto the site. If possible, a site safety engineer should routinely visit an ongoing drilling operation being run by the drilling subcontractor to observe safety practices and identify areas of concern.

It is extremely important that equipment entering a contaminated environment, or expected to encounter contamination, such as from drilling under tank farms, be in good working condition. All equipment should be inspected and operated prior to entry to the site to ensure it is working. If there is any doubt about the reliability of a piece of equipment, it should be replaced. For equipment that historically has a moderate to high failure rate (e.g. pumps, hoses, etc.), backup replacements should be readily available or on hand.

All downhole tools to be used should be checked to ensure threads are compatible and/or crossover subs are available.

Drilling Fluid/Contamination Containment

Prevention of and containment of spills is essential in all environments. Ground cover should be used to contain leaks and spills from the equipment. When spills occur, they should be cleaned up immediately to reduce the potential for spreading and to minimize waste generation. A typical containment system (3 mm plastic sheeting, lumber beams, and plywood pads for equipment) is not adequate for use at a "hot" site. The sheeting is too thin, easily torn, and worn through with the drill crew traffic. Hydraulic fluid leaks and spills can easily contaminate soils beneath the plastic and can also spread out over the surface of the plastic sheeting, eventually spreading the contaminants to traffic areas and onto the drill rig. Where such failures or leaks could occur, a containment system should be established which not only contains the spills, but also adequately isolates them, preventing them from spreading to clean areas. Traffic areas should be identified and kept clean.

In addition, containment should be established for the entire drilling location including where equipment is staged and any place that could come in contact with soils and/or fluids circulated from the borehole. Control zones should be identified and established to reduce personnel exposure. Equipment should be shielded or protected from potential contamination. The ground shielding should be of adequate strength to resist tearing and puncturing from drilling activities. The containment should be routinely inspected for breaches, and if found, repaired immediately. If a breech of the containment has resulted in a release, it should be cleaned up immediately. Equipment should be configured to increase safety and reduce the spread of contamination, and unnecessary tools/equipment should be removed from the exclusion site. For a radiological site, more permanent containment and decontamination structures should be considered. The drilling contractor should meet with an environmental engineering and design firm to develop preliminary drilling containment designs.

After the completion of the Activity Plan, a minimum of four months is needed for preparation before drilling begins. A Readiness Review at the site with the site personnel, the drilling contractor, and the EMWD team should take place approximately six weeks prior to the beginning of operations

Safety and Health Lessons Learned from Demonstrations

Areas have been identified as needing improvement to meet the needs of the environmental remediation customer. The following recommendations are suggested for review:

- Explore alternative drilling spoils removal options, such as air/foam drilling after the emplacement of casing to collect airborne spoils or use of a reduced mud system.
- Conduct a “cold” site demonstration to address those criteria not met or not tested. Conduct the demonstration as if it were a “hot” site demonstration. Areas to be addressed include:
  - Drill other formations (e.g., silt-rich sands and caliche-rich zone).
  - Show full functionality of the EMWD tool with the Tensor Steering Tool and TruTracker™ systems, or use only the EMWD tool with the TruTracker™ system.
  - Run the demonstration as a full “hot” site demonstration with appropriate safety, containment, and decontamination procedures.
  - Collect samples with a core tool and develop procedures for handling.
  - Use the TruTracker™ system to directionally drill under a Hanford-type tank to verify its capability.
- Conduct a “hot” site deployment addressing the following issues:
  - Permanent containment and decontamination structures.
  - Method for anchoring the drill rig.
- Map vadose zone contaminant plumes.

Comparison with Baseline and Alternative Technologies

The same operational safeguards and occupational safety and health recommendations apply to both baseline and alternative technologies. The alternative technology, EMWD, provides advance warning of contaminants, presently limited to certain gamma emitters. In addition, EMWD can be operated to minimize risk to site personnel by reducing IDW and steering around “hot” spots.

SECTION 7
REGULATORY AND POLICY ISSUES

Regulatory Considerations

No special permits are required for the operation of the HDD rigs to which the EMWD sensor system is coupled. Permitting for characterization of a site with EMWD should be less stringent than those required for conventional drilling and sample collection since environmental disturbance is reduced and IDW is significantly minimized.

Risks, Benefits, Environmental and Community Issues

All regulatory requirements for the use of EMWD should be similar or less stringent than those required for the baseline because the technology reduces the risk of exposure of workers to hazardous conditions and eliminates the need for the collection, shipment, and analysis of samples.

The use of EMWD reduces the environmental impact.

- Contact with contaminated soils and IDW can be minimized.
- Horizontal directional drilling requires fewer locations to characterize the subsurface than vertical drilling, and the holes can be sealed during retraction of the rods.
- The downhole EMWD components can easily be decontaminated with only a small volume of material.

The use of this technology eliminates the risk of exposure associated with the shipping and analysis of highly radioactive samples.

Community reaction should be positive due to the use of an environmentally friendly technology.

SECTION 8
LESSONS LEARNED

Implementation Considerations and Limitations

When an EMWD system is coupled with HDD, it is possible to explore the area under a contaminant source to determine the location, activity, and extent of a contaminant plume without further compromising the integrity of the contaminant source. As presently equipped with the GRS, EMWD provides a continuous and real-time source of data similar to the Spectral Gamma Probe (TechID 2364) that is used in vertical applications.

The use of EMWD is currently limited to sites where drilling can effectively penetrate the subsurface. Its use is restricted or impractical where contamination is located in challenging geologic environments such as in hard rock and heavily cobbled soils. Successful use is generally limited to clayey and sandy sediments. Sites that have radioactivity levels that span wide ranges may present problems for quantitative analyses for the NaI detector.

Technology Selection Considerations

The NaI detector used in the present EMWD system has a relatively high detection efficiency but has a relatively poor energy resolution and its light output varies with temperature. As a result, it is difficult to resolve gamma-ray peaks when signal-to-background ratios are relatively low. Higher resolution is currently achievable with a high purity germanium detector, but it cannot be used for downhole applications because it must be cooled to liquid nitrogen temperatures. Technology to improve future gamma probe sensors might include electronic components that do not undergo gain shifts with either temperature or counting rate and a higher resolution, ambient temperature detector.

APPENDIX A
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APPENDIX B
ACRONYMS AND ABBREVIATIONS

bps	bits per second (baud)
CMW	Charles Machine Works
Ci	Curie
cm	centimeter
Cs	cesium
DC	direct current
DOE	U. S. Department of Energy
DTTS	Drilling Technology Test Site
EMWD	Environmental Measurement While Drilling
ERDF	Environmental Restoration Disposal Facility
FM	frequency modulation
FRB	F-Area Retention Basin
ft.	feet
GRS	Gamma Ray Spectrometer
HDD	Horizontal Directional Drilling
Hz	Hertz
IC	integrated circuit
IDW	investigation-derived waste
K	potassium
LMHC	Lockheed Martin Hanford Corporation
m	meter
ma	milliamp
MCA	multichannel analyzer
MeV	million electron volts
MTLSS	Mock Tank Leak Simulation Site
NRZ	non-return to zero
OD	outside diameter
Pa	Pascal
PC	personal computer
pCi/g	picocuries per gram
PLA	programmable logic array
PMT	photomultiplier tube
PNNL	Pacific Northwest National Laboratory
RCRA	Resource Conservation and Recovery Act
RF	radio frequency
SNL	Sandia National Laboratories
Sr	strontium
SRS	Savannah River Site
SST	Single-shell Tank
TTL	transistor-transistor logic
TWRS	Tank Waste Remediation System
V	Volt
WSRC	Westinghouse Savannah River Company
WHC	Westinghouse Hanford Company